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SURVEYING OF BOREHOLES

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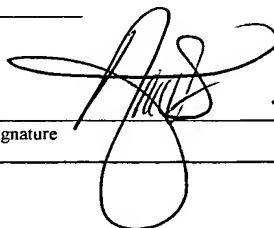
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SURVEYING OF BOREHOLES

1 This application is a continuation-in-part of Application
2 No. 10/072,129, filed 02/05/2002.

3 This invention relates to the surveying of boreholes,
4 and relates more particularly but not exclusively to
5 determining the true azimuth of a borehole.

6
7 When drilling a well for exploration and recovery of
8 oil or gas, it is known to drill a deviated well,
9 which is a well whose borehole intentionally departs
10 from vertical by a significant extent over at least
11 part of its depth. When a single drilling rig is
12 offshore, a cluster of deviated wells drilled from
13 that rig allows a wider area and a bigger volume to
14 be tapped from the single drilling rig at one time
15 and without expensive and time-consuming relocation
16 of the rig than by utilising only undeviated wells.
17 Deviated wells also allow obstructions to be by-
18 passed during drilling, by suitable control of the
19 deviation of the borehole as it is drilled. However,
20 to obtain the full potential benefits of well

1 deviation requires precise knowledge of the
2 instantaneous location and heading of the bottom-hole
3 assembly (including the drilling bit and steering
4 mechanisms such as adjustable stabilisers). Depth
5 of the bottom-hole assembly (or axial length of the
6 borehole) can be determined from the surface, for
7 example by counting the number of standard-length
8 tubulars coupled into the drill string, or by less
9 empirical procedures. However, determination of the
10 location and heading of the bottom-hole assembly
11 generally requires some form of downhole measurement
12 of heading. Integration of heading with respect to
13 axial length of the borehole will give the borehole
14 location relative to the drilling rig.

15
16 In this context, the word "heading" is being used to
17 denote the direction in which the bottom-hole
18 assembly is pointing (ie. has its longitudinal axis
19 aligned), both in a horizontal and vertical sense.
20 Over any length of the borehole which can be
21 considered as straight for the purposes of
22 directional analysis, the borehole axis in a deviated
23 well will have a certain inclination with respect to
24 true vertical. A vertical plane including this
25 nominally straight length of borehole will have a
26 certain angle (measured in a horizontal plane) with
27 respect to a vertical plane including a standard
28 direction; this standard direction is hereafter taken
29 to be true magnetic north, and the said angle is the
30 magnetic azimuth of the length of the borehole under
31 consideration (hereafter simply referred to as

1 "azimuth"). The combination of inclination and
2 azimuth at any point down the borehole is the heading
3 of the borehole at that point; borehole heading can
4 vary with depth as might be the case, for example,
5 when drilling around an obstacle.

6
7 Instrumentation packages are known, which can be
8 incorporated into bottom-hole assemblies to measure
9 gravity and magnetism in a number of orthogonal
10 directions related to the heading of the bottomhole
11 assembly. Mathematical manipulations of undistorted
12 measurements of gravitational and magnetic vectors
13 can produce results which are representative of the
14 true heading at the point at which the readings were
15 taken. However, the measurements of magnetic
16 vectors are susceptible to distortion, not least
17 because of the masses of ferrous materials
18 incorporated in the drill string and bottom-hole
19 assembly. Distortion of one or more magnetic vector
20 measurements can give rise to unacceptable errors in
21 the determination of heading, and undesirable
22 consequences. Distortion of magnetic vectors in the
23 region of the instrumentation arising from inherent
24 magnetism of conventional drill string and bottom-
25 hole assembly components can be mitigated by locating
26 the instrumentation in a special section of drill
27 string which is fabricated of non-magnetic alloy.
28 However, such special non-magnetic drill string
29 sections are relatively expensive. Moreover, the
30 length of non-magnetic section required to bring
31 magnetic distortion down to an acceptable level

1 increases significantly with increased mass of
2 magnetic bottom-hole assembly and drill string
3 components, with consequent high cost in wells which
4 use such heavier equipment, e.g. wells which are
5 longer and/or deeper. Hence such forms of passive
6 error correction may be economically unacceptable.
7 Active error correction by the mathematical
8 manipulation of vector readings which are assumed to
9 be error-free or to have errors which are small may
10 give unreliable results if the assumption is
11 unwarranted.

12

13 Before describing the invention, several definitions
14 will be detailed with reference to Figs. 1 and 2 of
15 the accompanying drawings, wherein:-

16

17 Fig. 1 is a schematic elevational view of the
18 bottom-hole assembly of a drill string; and

19

20 Fig. 2 is a schematic perspective view of
21 various axes utilised for denoting directions in
22 three dimensions.

23

24 Referring first to Fig. 1, the bottom-hole assembly
25 of a drill string comprises a drilling bit 10 coupled
26 by a non-magnetic drill collar 12 and a set of drill
27 collars 14 to a drill pipe 16. The drill collars 14
28 may be fabricated of a magnetic material, but the
29 drill collar 12 is substantially devoid of any self-
30 magnetism.

31

1 During local gravity and magnetic field vector
2 measurements, the non-magnetic drill collar 12 houses
3 a downhole instrumentation package schematically
4 depicted at 18. (In reality, the package 18 would
5 not be visible as is apparently the case in Fig. 1
6 since the package 18 is utilised within the interior
7 of the collar 12). The downhole instrumentation
8 package 18 is capable of measuring gravity vectors
9 and local magnetic vectors, for example by the use of
10 accelerometers and fluxgates respectively. The
11 instrumentation package 18 may be axially and
12 rotationally fixed with respect to the bottom-hole
13 assembly, including the drilling bit 10, whose
14 heading is to be determined; the instrumentation
15 package 18 would then be rigidly mounted in the
16 bottom-hole assembly, within the non-magnetic drill
17 collar 12 which is fabricated of non-magnetic alloy.
18 Alternatively, the package 18 could be lowered
19 through the collar 12, either on a wireline or as a
20 free-falling package, with internal recording of the
21 local gravity vectors and the local magnetic vectors.
22 The alternative procedures for measurement processing
23 according to whether the instrumentation package 18
24 is axially fixed or mobile will be subsequently
25 described.

26

27 Referring now to Fig. 2 for convenience of conceptual
28 presentation and calculation references, a
29 hypothetical origin or omni-axial zero point "0" is
30 deemed to exist in the centre of the instrumentation
31 package 18 (not shown in Fig. 2). Of the three

1 orthogonal axes OX, OY and OZ defining the alignment
2 of the instrumentation relative to the bottom-hole
3 assembly, the OZ axis lies along the axis of the
4 bottom-hole assembly, in a direction towards the
5 bottom of the assembly and the bottom of a borehole
6 20 drilled by the drilling bit 10. The OX and OY
7 axes, which are orthogonal to the OZ axis and
8 therefore lie in a plane 0.N2.E1 (now defined as the
9 "Z-plane") at right angles to the bottom-hole
10 assembly axis OZ, are fixed with respect to the body
11 (including the collar 12) of the bottom-hole
12 assembly. As viewed from above, the OX axis is the
13 first of the fixed axes which lies clockwise of the
14 upper edge of the (inclined) bottom-hole assembly,
15 this upper edge lying in the true azimuth plane
16 0.N2.N1.V of the bottom-hole assembly. The angle
17 N2.0.X. in the Z-plane 0.N2.E1 (at right angles to OZ
18 axis) between the bottom-hole assembly azimuth plane
19 0.N2.N1.V and the OX axis is the highside angle "HS".
20 The OY axis lies in the Z-plane 0.N2.E1 at right
21 angles to the OX axis in a clockwise direction as
22 viewed from above. A gravity vector-measuring
23 accelerometer (or other suitable device) is fixedly
24 aligned with each of the OX, OY and OZ axes. A
25 magnetic vector-measuring fluxgate (or other suitable
26 device) is fixedly aligned in each of the OX, OY and
27 OZ axes. The instrumentation package 18 may be
28 energised by any suitable known arrangement, and the
29 instrumentation readings may be telemetered directly
30 or in coded form to a surface installation (normally
31 the drilling rig) by any suitable known method, or

1 alternatively the instrumentation package 18 may
2 incorporate computation means to process
3 instrumentation readings and transmit computational
4 results as distinct from raw data, or the
5 instrumentation package 18 may incorporate recording
6 means for internal recording of the local axial
7 magnetic vectors for subsequent retrieval of the
8 package 18 and on-surface processing of the recorded
9 measurements.

10

11 Also notionally vectored from the origin O are a true
12 vertical (downwards) axis OV, a horizontal axis ON
13 pointing horizontally to true Magnetic North, and an
14 OE axis orthogonal to the OV and ON axes, the OE axis
15 being at right angles clockwise in the horizontal
16 plane as viewed from above (ie. the OE axis is a
17 notional East-pointing axis).

18

19 The vertical plane O.N2.N1.V including the OZ axis
20 and OV axis is the azimuth plane of the bottom-hole
21 assembly. The angle V.O.Z. between the OV axis and
22 the OZ axis, ie. the angle in the bottom-hole
23 assembly azimuth plane O.N2.N1.V, is the bottom-hole
24 assembly inclination angle "INC" which is the true
25 deviation of the longitudinal axis of the bottom-hole
26 assembly from vertical. Since the angles V.O.N1 and
27 Z.O.N2 are both right angles and also lie in a common
28 plane (the azimuth plane O.N2.N1.V), it follows that
29 the angle N1.O.N2 equals the angle V.O.Z, and hence
30 the angle N1.O.N2 also equals the angle "INC".

1 The vertical plane O.N.V including the OV axis and
 2 the ON axis is the reference azimuth plane or true
 3 Magnetic North. The angle N.O.N1 measured in a
 4 horizontal plane O.N.N1.E.E1 between the reference
 5 azimuth plane O.N.V. (including the OV axis and the
 6 ON axis) and the bottom-hole assembly azimuth plane
 7 O.N2.N1.V (including the OV axis and the OZ axis) is
 8 the bottom-hole assembly azimuth angle "AZ".

9
 10 The OX axis of the instrumentation package is related
 11 to the true Magnetic North axis ON by the vector sum
 12 of three angles as follows:-

13
 14 (1) horizontally from the ON axis round Eastwards
 15 (clockwise as viewed from above) to a horizontal axis
 16 O.N1 in the bottom-hole assembly azimuth plane
 17 O.N2.N1.V by the azimuth angle AZ (measured about the
 18 origin O in the horizontal plane);

19
 20 (2) vertically upwards from the horizontal axis O.N1
 21 in the azimuth plane O.N2.N1.V to an inclined axis
 22 O.N2 in the Z-plane (the inclined plane O.N2.E1
 23 including the OX axis and the OY axis) by the
 24 inclination angle INC (measured about the origin O in
 25 a vertical plane including the origin O); and

26
 27 (3) a further angle clockwise/Eastwards (as defined
 28 above) in the Z-plane from the azimuth plane to the
 29 OX axis by the highside angle HS (measured about the
 30 origin O in the inclined Z-plane O.N2.E1 which
 31 includes the origin O).

1 Borehole surveying instruments measure the two
2 traditional attitude angles, inclination and azimuth,
3 at points along the path of the borehole. The
4 inclination at such a point is the angle between the
5 instrument longitudinal axis and the Earth's gravity
6 vector direction (vertical) when the instrument
7 longitudinal axis is aligned with the borehole path
8 at that point. Azimuth is the angle between the
9 vertical plane which contains the instrument
10 longitudinal axis and a vertical reference plane
11 which may be either magnetically or gyroscopically
12 defined; this invention is concerned with the
13 measurement of azimuth defined by a vertical
14 reference plane containing a defined magnetic field
15 vector.

16
17 Inclination and azimuth (magnetic) are conventionally
18 determined from instruments which measure the local
19 gravity and magnetic field components along the
20 directions of the orthogonal set of instrument-fixed
21 axes (OX,OY,OZ); traditionally, OZ is the instrument
22 longitudinal axis. Thus, inclination and azimuth
23 are determined as functions of the elements of the
24 measurement set (GX,GY,GZ,BX,BY,BZ), where GX is the
25 magnitude of the gravity vector component in
26 direction OX, BX is the magnitude of the magnetic
27 vector component in direction OX, etc. The
28 calculations necessary to derive inclination and
29 azimuth as functions of GX,GY,GZ,BX,BY,BZ are well
30 known.

31

1 When the vertical magnetic reference plane is defined
2 as containing the local magnetic field vector at the
3 instrument location, the corresponding azimuth angle
4 is known as the raw azimuth; if the vertical magnetic
5 reference plane is defined as containing the Earth's
6 magnetic field vector at the instrument location, the
7 corresponding azimuth angle is known as absolute
8 azimuth.

9
10 In practice, the value of the absolute azimuth is
11 required and two methods to obtain it are presently
12 employed:

13
14 (i) The instrumentation package is contained
15 within a non-magnetic drill collar (NMDC)
16 which is sufficiently long to isolate the
17 instrument from magnetic effects caused by
18 the proximity of the drill string (DS)
19 above the instrument and the stabilizers,
20 bit, etc. forming the bottom-hole assembly
21 (BHA) below the instrument. In this case
22 the Earth's magnetic field is uncorrupted
23 by the DS and BHA and the raw azimuth
24 measured is equal to the absolute azimuth.

25
26 (ii) The corrupting magnetic effect of the DS
27 and BHA is considered as an error vector
28 along direction OZ thereby leaving BX and
29 BY uncorrupted (components only of the
30 Earth's magnetic field). The calculation
31 of the absolute azimuth can then be

1 performed as a function of
2 GX,GY,GZ,BX,BY,Be, where Be is some value
3 (or combination of values) associated with
4 the Earth's magnetic field..
5

6 The error in the measurement of absolute azimuth by
7 method (ii) is dependent on the attitude of the
8 instrument and may greatly exceed the error in the
9 measurement of the raw azimuth; the reasons for this
10 are summarised as follows:
11

- 12 (iii) the need to know the values of Earth's
13 magnetic field components in instrument-
14 magnetic-units to a high degree of
15 accuracy:
- 16 (iv) an inherent calculation error due to the
17 availability of only the uncorrupted cross-
18 axis (BOXY) magnetic vector component.
19 [This is analogous to measuring only the
20 gravity component GZ and then attempting to
21 determine the inclination (INC) from $INC =$
22 $ACOS (GZ)$, with the magnitude of Earth's
23 gravity = 1 instrument gravity-unit].
24

25 The foregoing text and Figs. 1 and 2 were extracted
26 from the introduction to GB2229273A, which represents
27 the state of the art over which the present invention
28 is an improved method of surveying of boreholes, as
29 will be detailed below.
30

1 Recent developments of long-reach directional rotary
2 drilling systems make it desirable to be able to
3 perform accurate near-bit survey measurements.
4 While it is possible to make the relatively short
5 bottom-hole drilling system (comprising the drill
6 bit, downhole drill motor, and possibly also an
7 adjustable stabiliser) substantially non-magnetic,
8 the corruption of magnetic field measurements in a
9 near-bit survey instrument package can only be
10 eliminated by the use of long non-magnetic drill
11 collars, or through the use of calculation correction
12 methods which require measurements of absolute
13 magnetic fields (as described in GB2229237A) and are
14 unsatisfactory for some drilling directions at high
15 inclinations.

16
17 The present invention allows the accurate measurement
18 of azimuth at a near-bit location in a bottom-hole
19 assembly using only a standard-length non-magnetic
20 drill collar (ie. a non-magnetic drill collar with a
21 standard length of 30 metres).

22
23 According to a first aspect of the present invention
24 there is provided a method of surveying the magnetic
25 azimuth of a borehole penetrated by a bottom-hole
26 assembly comprising a magnetic drill string attached
27 to one end of a substantially non-magnetic drill
28 collar to the other end of which is attached a
29 substantially non-magnetic drilling bit assembly, by
30 deriving the true magnitude of the terrestrial
31 magnetic field BZe in the direction of the

1 longitudinal axis OZ of the borehole in the region of
2 the substantially non-magnetic drill collar, said
3 method comprising the steps of measuring the
4 longitudinal magnetic field $BZ(a)$ (the component of
5 the magnetic field B in the direction OZ) at a single
6 predetermined point along the length of the
7 substantially non-magnetic drill collar, and
8 measuring the longitudinal magnetic field $BZ(b)$ at a
9 single predetermined point along the length of the
10 substantially non-magnetic drilling bit assembly, to
11 provide a longitudinal-position-dependent pair of
12 longitudinal magnetic field measurements $BZ(z)$, and
13 calculating BZe on the basis that $BZ(z) = BZe + E(z)$,
14 where $E(z)$ is the longitudinal-position-dependent
15 longitudinal magnetic field error induced by
16 magnetism of the drill string on the assumption that
17 the longitudinal magnetic field error $E(z)$ is induced
18 by a single notional magnetic pole in the magnetic
19 drill string substantially at the attachment of the
20 magnetic drill string to the substantially non-
21 magnetic drill collar.

22

23 The foregoing magnetic azimuth surveying method may
24 optionally be extended to include the measurement of
25 gravity vector components Gx , Gy and Gz and solving
26 the function $[Gx, Gy, Gz, Bx, By, BZe]$ to determine the
27 borehole heading.

28

29 Other aspects of the present invention provide
30 apparatus for use in the foregoing method, and

1 borehole drilling and surveying equipment
2 incorporating such apparatus.

3
4 Embodiments of the invention will now be described by
5 way of example, with reference to Fig. 3 of the
6 accompanying drawings, which is a schematic diagram
7 of a bottom-hole assembly to which the invention is
8 applied.

9
10 Referring to Fig. 3, a bottom-hole assembly 100
11 comprises a drilling bit assembly 102, a non-magnetic
12 drill collar 104, and a drill string 106.

13
14 The drilling bit assembly 102 comprises a drilling
15 bit 108 and a downhole drilling motor 110. The
16 assembly 102 is fabricated of non-magnetic materials,
17 and is therefore substantially free of self-
18 magnetism. A direction-controlling stabiliser (not
19 shown) which is also free of self-magnetism may be
20 incorporated in the drilling bit assembly 102 in
21 order to control the directional tendency of further
22 extensions of the borehole (not depicted per se)
23 drilled by the drilling bit 108, such directional
24 tendency being normally controlled or influenced by
25 the results of borehole surveying in conjunction with
26 intended borehole targets (with possible directional
27 modifications to mitigate unexpected problems).

28
29 The non-magnetic drill collar 104 is a standard
30 component known per se, being fabricated of non-

1 magnetic materials and having a standard length of
2 ten metres.

3

4 The drill string 106 is a standard assembly of hollow
5 tubular steel pipes interconnected by tapered screw-
6 thread connections to form a mechanical and hydraulic
7 link with a drilling rig (not shown) on the surface
8 of land or sea above the borehole. Since the drill
9 string 106 is fabricated mainly or wholly of ferrous
10 materials, it has self-magnetism which corrupts at
11 least the longitudinal component of magnetic field
12 measurements performed in the bottom-hole assembly
13 100 near the drilling bit 108.

14

15 The upper end 112 of the drilling bit assembly 102 is
16 attached to the lower end 114 of the non-magnetic
17 drill collar 104. The upper end 116 of the non-
18 magnetic drill collar 104 is attached to the lower
19 end 118 of the drill string 106.

20

21 For the purpose of near-bit borehole azimuth
22 surveying in accordance with the invention, the
23 bottom-hole assembly 100 is fitted at mutually
24 spaced-apart locations with two separate survey
25 instruments, as will now be detailed.

26

27 A near-bit survey instrument ("NBSI") 120 is fitted
28 within the substantially non-magnetic drilling bit
29 assembly 102 at a location (designated "B") which is
30 at a known fixed distance "b" below the lower end 118
31 of the drill string 106. (The term "below" is used

1 to indicate that the location "B" is closer to the
2 drilling bit 108 and hence further along the borehole
3 from the surface than the lower end 118 of the drill
4 string 106 notwithstanding that the borehole may have
5 deviated so far from an initially vertically
6 downwards direction at the surface that the borehole
7 is now horizontal or even headed upwards).

8
9 A second survey instrument ("SSI") 122 is fitted
10 within the non-magnetic drill collar 104 at a
11 location (designated "A") which is at a known fixed
12 distance "a" below the lower end 118 of the drill
13 string 106. (The term "below" is again used to
14 indicate that the location "A" is closer to the
15 drilling bit 108 and hence further along the borehole
16 from the surface than the lower end 118 of the drill
17 string 106, in the same way that "below" was used in
18 respect of location "B" as detailed above).

19
20 The borehole surveying method in accordance with the
21 invention is based on the assumption that the
22 magnetic survey-corrupting effects of the drill
23 string 106 can be represented by a single notional
24 magnetic pole of longitudinal magnetic strength "m"
25 and which is located at the lower end 118 of the
26 drill string 106. Details of the method of the
27 invention, as based on this assumption, will now be
28 given.

29
30 If the NBSI 120 and the SSI 122 each contain
31 conventional 3-orthogonal-axes gravity (G) and

1 magnetic (B) transducers then for this configuration,
 2 the measured parameters set for the NBSI 120 at
 3 position A can be defined by :-

$$4 \quad \{GXa, GYa, GZa, BXa, BYa, BZa\} = \{GX, GY, GZ, BX, BY, BZa\}$$

6
 7 and that for the SSI 122 at position B by :-

$$8 \quad \{GXb, GYb, GZb, BXb, BYb, BZb\} = \{GX, GY, GZ, BX, BY, BZb\}$$

10

11 In terms of the conventional Highside, Inclination
 12 and Azimuth surveying angles, the corresponding
 13 survey parameter sets are defined by :-

14

$$15 \quad \{HS, INC, AZa\} \text{ and } \{HS, INC, AZb\}$$

16

17 Conventional derivations for the Azimuth Angle (AZ)
 18 lead to calculations of AZa and AZb from :-

19

$$20 \quad \sin(AZa)/\cos(AZa) = K1/(K2*BZa + K3)$$

21

$$22 \quad \text{and } \sin(AZb)/\cos(AZb) = K1/(K2*BZb + K3)$$

23

24 where K1, K2, and K3 are functions of only INC, HS, BX,
 25 and BY.

26

27 The corrected azimuth AZc is given by :-

28

$$29 \quad \sin(AZc)/\cos(AZc) = K1/(K2*BZ + K3)$$

30

31 where $BZ = BZa - Ea = BZb - Eb$

32 with $Ea = m/a^2$ = the magnetic error at A due to pole m

1 and $E_b = m/b^2$ = the magnetic error at B due to pole m .

2

$$3 \quad \text{Thus,} \quad K_2 \cdot BZ + K_3 = K_1 \cdot \cot(AZ_c)$$

$$4 \quad K_2 \cdot BZ + K_3 + K_2 \cdot E_a = K_1 \cdot \cot(AZ_a)$$

$$5 \quad K_2 \cdot BZ + K_3 + K_2 \cdot E_b = K_1 \cdot \cot(AZ_b)$$

6

7 which yield :-

8

$$9 \quad E_a = (K_1/K_2) \cdot [\cot(AZ_a) - \cot(AZ_c)] = m/a^2$$

10

$$11 \quad \text{and} \quad E_b = (K_1/K_2) \cdot [\cot(AZ_b) - \cot(AZ_c)] = m/b^2$$

12

13 Therefore :-

14

$$15 \quad a^2 \cdot [\cot(AZ_a) - \cot(AZ_c)] = b^2 \cdot [\cot(AZ_b) - \cot(AZ_c)]$$

16

$$17 \quad \text{or} \quad \cot(AZ_c) \cdot (b^2 - a^2) = b^2 \cdot \cot(AZ_b) - a^2 \cdot \cot(AZ_a)$$

18

19 Thus it can be shown that the corrected azimuth AZ_c
20 can be derived from (for example)

21

$$22 \quad \sin(AZ_c) / \cos(AZ_c) = (b^2 - a^2) \cdot \sin(AZ_a) \cdot \sin(AZ_b) /$$

$$23 \quad [b^2 \cdot \sin(AZ_a) \cdot \cos(AZ_b) - a^2 \cdot \sin(AZ_b) \cdot \cos(AZ_a)]$$

24

25 or from other equivalent functions of a, b, AZ_a , and
26 AZ_b alone.

27

28 Modifications and variations of the above-described
29 surveying method, and of the instrumentation
30 therefor, can be adopted without departing from the
31 scope of the invention. For example, the survey
32 instruments 120 and 122 could be simplified to

1 measure only the longitudinal (Z-axis) magnetic
2 fields at their respective locations "B" and "A",
3 with other instrumentation being utilised to measure
4 one or more of the omitted parameters if such
5 measurements are deemed necessary or desirable.

6
7 Another possible, although less practicable,
8 modification is to replace the two magnetic sensors
9 at fixed locations with a single sensor which is
10 transferred or reciprocated between these two
11 locations, with the magnetic field at each being
12 sampled for further processing. This would result in
13 two non-simultaneous readings, but the time
14 difference would not be significant to the method of
15 the invention provided it is small in relation to
16 movement of the drill string.

17
18 Other modifications and variations can be adopted
19 without departing from the scope of the invention as
20 defined in the claims.